Feasibility of Capturing and Returning Small Near-Earth Asteroids

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This paper describes an investigation into the technological feasibility of finding, characterizing, robotically capturing, and returning an entire Near-Earth Asteroid (NEA) to the International Space Station (ISS) for scientific investigation, evaluation of its resource potential, determination of its internal structure and other aspects important for planetary defense activities, and to serve as a testbed for human operations in the vicinity of an asteroid. Reasonable projections suggest that several dozen candidates NEAs in the size range of interest (~2-m diameter) will be known before the end of the decade from which a suitable target could be selected. The conceptual mission objective is to return a ~10,000-kg asteroid to the ISS in a total flight time of approximately 5 years using a single Evolved Expendable Launch Vehicle. Preliminary calculations indicate that this could be accomplished using a solar electric propulsion (SEP) system with high-power Hall thrusters and a maximum power into the propulsion system of approximately 40 kW. The SEP system would be used to provide all of the post-launch ΔV. The selected asteroid would have an unrestricted Earth return Planetary Protection categorization, and would be curated at the ISS where numerous scientific and resource utilization experiments would be conducted. Asteroid material brought to the ground would be curated at the NASA Johnson Space Center. This preliminary study identified several areas where additional work is required, but no show stoppers were identified for the approach that would return an entire 10,000-kg asteroid to the ISS in a mission that could be launched by the end of this decade. Alternative mission concepts in which the NEA is returned to a high-Earth orbit suggest that the same 40-kW flight system, beginning with an Atlas V 521-class launch, may be capable of returning a 500,000 kg asteroid with a total flight time of 5 years. This is an astonishing 35-to-1 mass amplification. Scaling this up in power by an order-of-magnitude, to SEP systems of order 400 kW, may provide the capability to return entire asteroids in the 5,000,000-kg range to high-Earth orbit using a heavy-life launch vehicle.

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Introduction

Advances in propulsion technology have always enabled new capabilities, capabilities that were unheard of or inconceivable in previous generations. Steam engines, internal combustion engines, jet engines, and chemical rocket engines have all revolutionized the world. High-power solar electric propulsion systems now hold this promise. With power levels of tens to hundreds of kilowatts, such systems are like a shiny new toy with applications are just starting to be investigated. In this paper we examine the feasibility of using high-power solar electric propulsion to return an entire Near-Earth Asteroid (NEA) to the vicinity of the Earth. The paper describes a study that was conducted to investigate the technical feasibility of identifying, capturing, and returning to the International Space Station (ISS) an entire NEA for scientific investigation and evaluation of its resource potential. With a targeted launch by the end of this decade, this mission concept would capture the imagination of the public like few others. The newly selected OSIRIS-REx New Frontiers mission[1] seeks to return approximately 60 grams of material from a near-Earth asteroid by 2023. The Apollo program returned 382 kg of moon rocks in six missions. The mission concept described in this paper seeks to return an entire NEO, with ~10,000 kg of extraterrestrial material, in a single mission by 2025. Such an extraordinary sample would provide a wealth of scientific and engineering information. It could potentially jump start a whole industry dealing with extraterrestrial resource utilization, provide valuable information about the structure of asteroids and other characteristics important for planetary defense, and could be the first step in the realization of the vision of exploiting the natural resources in space to revolutionize the world.[2-4]

This is exactly the right time to investigate the feasibility of this mission. The capability for identifying sufficiently small NEOs is just becoming or is projected to become available in the next few years as are sufficiently large solar electric propulsion systems that hold the promise of being able to return an entire small NEO to low Earth orbit with a reasonable flight-time. Furthermore, the ISS would make an ideal platform for experimenting on this object in the pristine space environment and would eliminate the need to return the entire object to the Earth's surface while enabling the return of selected samples to the ground for detailed analysis. We are assuming here that ISS operations would continue beyond 2025.

Reasonable projections suggest that several dozen candidate NEOs of the right size (i.e., sufficiently small that they can be readily transported) will be known before the end of the decade from which a suitable, unrestricted Earth return target could be selected. One of our key self-imposed mission objectives includes the determination of whether it is possible return the entire asteroid in a total flight time of approximately five years using a single launch by an Evolved Expendable Launch Vehicle (EELV). John Lewis also says[5] in *Mining the Sky*, "Like all other endeavors so far attempted in space, the limiting factor on profitability of space resource use is transportation cost." We assumed the use of solar electric propulsion (SEP) for all of the post-launch ΔV with the expectation that this would provide the lowest transportation cost. The flight time constraint of five years from launch to return to the ISS, along with the asteroid mass of ~10,000 kg determine the SEP power level. Therefore, one of the key objectives became the determination of this power level. The mission concept uses the SEP system to escape from Earth orbit and rendezvous with the small NEO. Once at the NEO the spacecraft instrumentation determines the spin state of the asteroid. The spacecraft would then match this spin state, capture the asteroid, and despin the combined asteroid and spacecraft. Finally, the SEP system would be used to perform the heliocentric transfer back to the Earth and spiral down to rendezvous and dock with the ISS. The asteroid would be curated at the ISS where numerous scientific and resource utilization experiments would be conducted. Asteroid material brought to the ground would be curated at the NASA Johnson Space Center where subsamples would be prepared and distributed to laboratories worldwide for testing and analysis.

If higher-power SEP vehicles are developed, such as the 300-kW-class vehicle envisioned to support the human exploration of near Earth asteroids,[6] then the return of 100,000-kg-class asteroids may become feasible.

A. Objectives

The objective of this study is to investigate the feasibility of an Asteroid Return Mission requiring the identification and characterization of a scientifically interesting NEO with a mass of approximately 10,000 kg, and the launch of a spacecraft by the end of the decade that could rendezvous with, capture, and return this asteroid to the ISS with a total flight time of approximately five years from a single evolved expendable launch vehicle (EELV). In this mission concept the ISS would serve as the curatorial facility for the extraterrestrial material as well as a "geology" laboratory and test-bed for learning how to handle, process, and subsample asteroid material in space. This application of the ISS would enable NASA and the international community to begin to assess the resource potential of NEOs for exploration and commercial use. Detailed analysis would provide key data to relate meteorites to asteroids, quantify the effects of space weathering, and provide information important to planetary defense.

B. Feasibility Issues

The mass of an asteroid as a function of its diameter (assuming a spherical asteroid) is given in **Table 1** for a reasonable range of likely bulk densities[7] (1.5 to 3.5 g/cm3). It is clear from this table that even very small asteroids are quite massive from the perspective of transporting them back to the ISS. A 10,000-kg asteroid is likely to be between only 1.5 and 2.5 m in diameter.

Table 1. Asteroid mass vs. diameter for densities of 1.5 g/cm^3, 2.5 g/cm^3 and 3.5 g/cm^3 (highlighted value used in subsequent feasibility analyses).

Asteroid Diameter (m)	Asteroid Mass (kg)		
	1.5 g/cm^3	2.5 g/cm^3	3.5 g/cm^3
1.0	785	1,309	1,833
2.0	6,283	10,472	14,661
3.0	21,206	35,343	49,480
4.0	50,265	83,776	117,286
5.0	98,175	163,625	229,074
6.0	169,646	282,743	395,841
7.0	269,392	448,986	628,580
8.0	402,124	670,206	938,289
9.0	572,555	954,259	1,335,962
10.0	785,398	1,308,997	1,832,596
11.0	1,045,365	1,742,275	2,439,185
12.0	1,357,168	2,261,947	3,166,725
13.0	1,725,520	2,875,866	4,026,213
14.0	2,155,133	3,591,888	5,028,643
15.0	2,650,719	4,417,865	6,185,011

The key feasibility issues for a mission intending to return an entire near-Earth asteroid to the ISS include:

1. Is it possible to identify and characterize sufficiently small and scientifically interesting candidate asteroids for return to the ISS?
2. How could the asteroid, which is a non-cooperative object, be captured, secured to the spacecraft, and despun while in deep-space?
3. Are there low-thrust trajectories that would be consistent with returning a 10,000-kg asteroid in a total flight time of ~5 years with reasonable SEP power levels and a single EELV launch?
4. Are there solar electric propulsion system technologies projected to be available this decade that would be consistent with the low-thrust trajectory analysis?
5. Would the overall flight system mass be consistent with a single EELV launch?
6. It is feasible to approach and dock a spacecraft containing a 10,000-kg asteroid with this ISS?
7. Could a 10,000-kg asteroid be safely handled at the ISS?

8. How would you curate an entire Asteroid at the ISS? What scientific investigations could/should be performed onboard the ISS, and what investigation should be performed on the ground?

II. Results

A. Asteroid Identification

Comets and asteroids that reach a perihelion of 1.3 AU or less are defined as near-Earth objects. The vast majority of these objects are rocky asteroids or so-called near-Earth asteroids (NEAs). Roughly 20% of the NEO population can approach the Earth's orbit to within 0.05 AU and these objects are defined as potentially hazardous objects (PHOs). According to the existing size frequency distribution for near-Earth asteroids, the rough number of these objects two meters and larger is one billion with 20% of this population reaching within 0.05 AU of the Earth's orbit. It is this latter population that would be most accessible in terms of a spacecraft rendezvous. At a minimum, there are several tens of millions of small undiscovered NEAs that would be accessible via spacecraft missions and meet the criteria for capturing and returning to the ISS. The difficulty is that asteroids of this small size are very difficult to discover and track with the existing one-meter aperture class, ground-based telescopes.

The key parameter in finding a suitable one to two meter-sized target body to bring back to the ISS is the mean albedo (reflectivity). For most NEAs the albedo is approximately 25%. For NEAs 1.7 meters in diameter or less, a near-Earth asteroid would have an absolute magnitude of 31 or fainter. There are currently four discovered objects that meet this criterion and all were subsequently lost and must be re-discovered. These objects can only be observed or discovered when they are very close to Earth. These four were all discovered less than 0.005 AU from the Earth. Current meter-class search telescopes are used to discover these objects. By far the most effective search program to date has been the Catalina Sky Survey (CSS) operating near Tucson AZ. When comparing the search efficiency of a NEO telescope, one usually computes the so-called etendu or the product of the telescope aperture and the field of view. For CSS the etendu is ~2. Larger search telescopes would be required to find and track objects of the size of interest for the Asteroid Return Mission concept.

Future search telescopes include the Panoramic Survey Telescope and Rapid Response System 1 (PanSTARRS 1) on Haleakala in Maui, Hawaii, which hopes to reach an etendu of 13 when it becomes fully operational. In addition, there is PanSTARRS 4 (4 x PanSTARRS 1)[8], which will have an etendu of ~51, and the Large Synoptic Survey Telescope (LSST)[9], which will be a 8.4 meter aperture wide field telescope in Chile that hopes for first light in 2018. The etendu for LSST is ~321 so it will be ~150 times more efficient at finding NEOs than CSS. Roughly speaking then, in about 2025, the number of discovered suitable targets whose diameters are less than 2 meters is expected be about 150 times more than today (about 4 x 150 = 600).

Since finding these small objects would not be easy even for the next generation of search telescopes, we can probably predict a linear discovery rate in the period from 2018 to 2025 so after the LSST telescope begins operations in 2019, we should expect about 85 objects 1.7 meters or less by the end of 2019 (600 total objects in 2025 divided by 7 years between 2018 and 2025) and another 85 objects by the end of 2020 etc.

Inferring the size/mass of these bodies demands that their spectral class be determined during the discovery period – when the object is bright. If this is done then the albedo can be inferred to the ~25% level. Then the diameter would be uncertain by a factor 1.12 or so and the mass uncertain by a factor of 1.4. If no spectral data are forthcoming, then the range of albedos for near-Earth objects is 0.04 to 0.6 with a mean of ~0.25. In this latter case then, the uncertainty in diameter could be as large as a factor of 4 with a corresponding uncertainty in mass of 64. The bulk density is also uncertain so if we have a spectral class, then the uncertainty in bulk density would be a factor of ~1.5. Without the spectral class, the uncertainty in bulk density could be a factor of ~2.5.

If we insist upon visiting a C- or D-class asteroid with low albedos, then the number of potential targets would be on the order of 150. In some regards, low albedo objects might be more scientifically interesting than the higher albedo S-type asteroids. The low albedo C and D types could have hydrated minerals and organics that would be of great interest to the scientific community since they would allow scientists to address the issue of whether these types of asteroids brought to the early Earth much of the water and carbon-based materials that allowed life to form. Asteroids with hydrated minerals could also be mined to produce hydrogen and oxygen (rocket fuel). S-types are thought to be primarily silicate rocks.

Water resources could be identified in D-type asteroids (possible ex-comets) or C-type asteroids by looking for the 3-micron spectral reflectance band that indicates hydrated minerals. About two thirds of the C-types do have hydrated minerals. D-type asteroids are rare in the near-Earth population. C-types make up about 50% of this population. In order to determine an object's spectral type, one needs to have a fairly bright object. For example, an object needs to get to 17.5 apparent magnitude for the Infrared Telescope Facility (IRTF) telescope to determine its spectral type and to determine the presence of the 3-micron band. That being the case, we doubt that we would have any 1-2 meter sized asteroids whose spectral characteristics could be determined in the next few years.

In the future when the next generation NEA surveys are underway (e.g., Pan-STARRS and LSST), one would have to get spectral characterization during the discovery period when the object was presumably very close – and hence bright. In addition, the newly discovered objects will need to be observed for more than a few days to secure their orbits. For those discovered objects that allow radar astrometric data, their orbits will be secured rapidly. Hence future potential small NEA mission targets would need to be discovered during upcoming close Earth approaches and they would need to have immediate follow-up observations to both refine their orbits and characterize their spectral class (e.g., C, D, S types).

B. Asteroid Capture

One of the new components to be developed for this proposed mission would be the device for capturing the asteroid and securing it to the spacecraft for the return trip. In order to have a well defined center-of-mass location for the asteroid attached to the spacecraft a system that results in rigid attachment would be required. The problem capture would be simplified if the target is a single-axis rotator with a rate < 1 rpm (most are slower). A sketch of a capture device conceptually designed for such a target is shown in Fig. 1. This conceptual approach should work whether the asteroid is a solid body or a rubble pile. The capture process concept is as follows:

1. After rendezvousing with the target body the spacecraft would observe it to establish the spin state (known roughly from pre-mission observations).
2. The spacecraft would approach in line with the pole and spins up to match the rotation rate of the target.
3. The spacecraft would move in slowly to enclose the target in the canister. The canister would be oversized to accommodate the uncertainty in the physical size of the asteroid.
4. The floating drawstring motor would pull the bag around the target, securing it tightly to the spacecraft. The canister would have a recloseble cover that would be used as a secondary containment for loose asteroid debris. After the asteroid is inside the canister, the cover would be closed and remain closed for the remainder of the mission.
5. The spacecraft would use the hydrazine reaction control subsystem (RCS) to despin the asteroid and spacecraft.

Additional work is needed to establish the probability of finding a single-axis rotator as a target and to investigate procedures for the capture of non-principal-axis rotators.

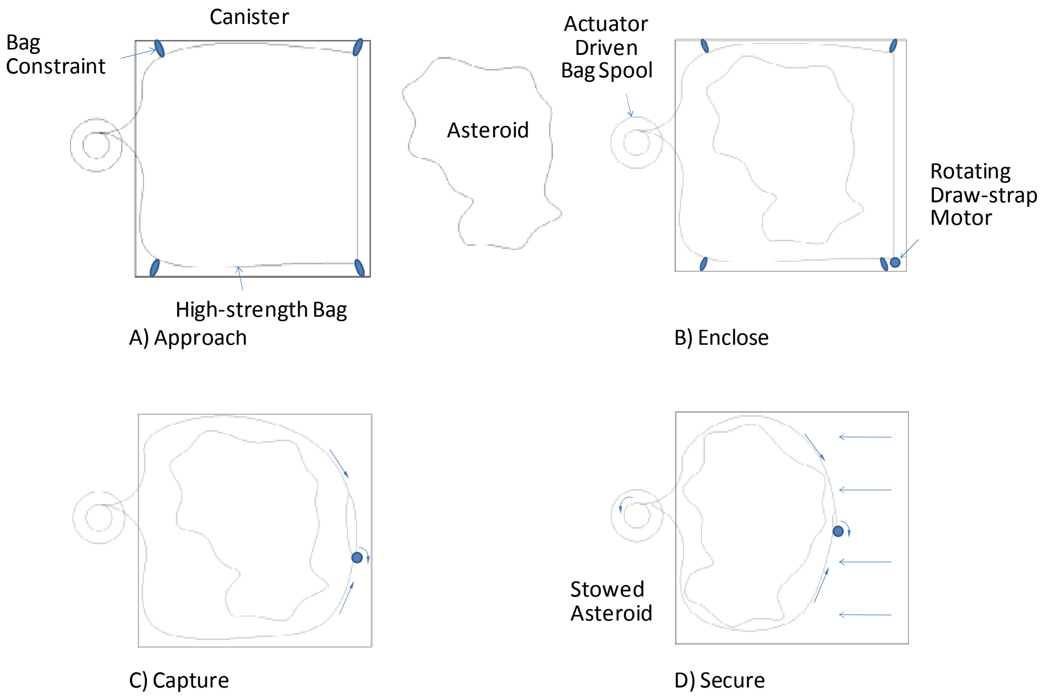

Fig. 1. Conceptual design of the asteroid capture system.

C. Low-Thrust Trajectory Analysis

Two low-thrust trajectory options were examined. In the first option, the mission would begin by launching to low Earth orbit (LEO) assuming launch vehicle performance equivalent to an Atlas V 521. The second option assumes the spacecraft would be launched to a GEO transfer orbit (GTO). This option would be more demanding on the launch vehicle, but would reduce the time of the initial Earth-departure spiral. The launch mass to GTO used in our trajectory analysis is consistent with the performance of a Delta IV Heavy-class launch vehicle. In both options the SEP subsystem, using high-power Hall thrusters, would provide all of the post-launch ΔV.

The conceptual design of the SEP subsystem is based on the use of four simultaneously operating, 10-kW, xenon Hall thrusters. The Hall thruster performance used in the trajectory analysis was estimated from the values for high performance thrusters developed recently that operate at power levels of 4.5 kW to over 12 kW. The assumed throttling profile is given in Fig. 2.

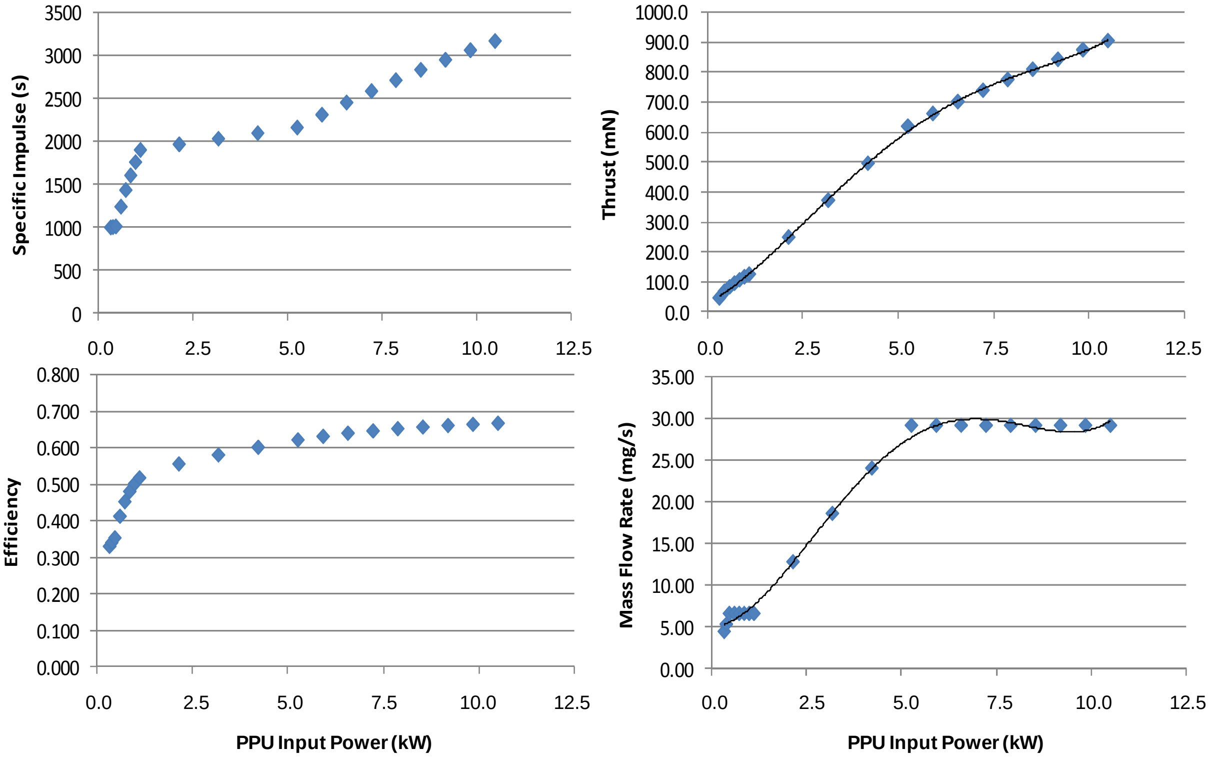

Fig. 2. Performance of the 10-kW Hall thrusters used in the trajectory analysis.

JPL's low-thrust trajectory software tools were used to calculate the SEP trajectories. For option 1 starting from LEO the spacecraft would reache the vicinity of the Moon after approximately 569 days. A lunar gravity assist (with a flyby altitude of ~100 km) would inject the craft onto an interplanetary trajectory with $C_3 < 2$ km^2/s^2. The spacecraft would continue thrusting for another 152 days to rendezvous with the asteroid. A total of 90 days are allotted for proximity operations to characterize and ultimately capture the asteroid. The spacecraft would then resume cruising with the SEP subsystem and targets the Earth-Moon system where another lunar gravity assist would be used to capture the spacecraft from $C_3 < 2$ km^2/s^2 to $C_3 = -1$ km^2/s^2. Once captured in Earth orbit the SEP subsystem would continue thrusting to spiral the spacecraft/asteroid down to the ISS orbit for a total flight time of 1983 days (5.4 years). A representative trajectory is given in Fig. 3. Since there are no known orbits for a sufficiently small NEO, we selected a known asteroid (1991 VG) with an Earth-like orbit (a = 1.027 AU, e = 0.04910, i = 1.446 deg) and used this case as a trajectory proof-of-concept. Once a population of feasibly small asteroids with Earth-like orbits is identified the expectation is that a suitable target could be chosen for the timeframe of interest. The trajectory for option 2, with a launch to GTO, is given in Fig. 4. The total flight time in this case would be 4.3 years.

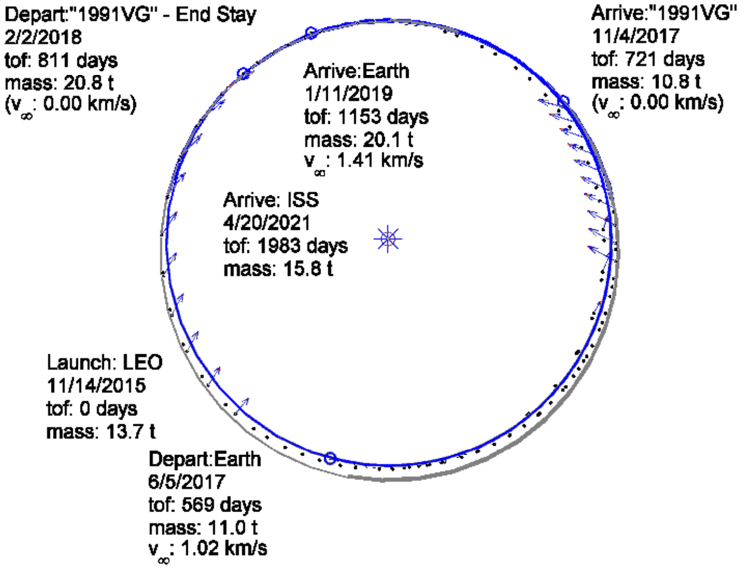

Fig. 3. Example trajectory to a “representative” NEA for a spacecraft with a 40-kW SEP system. When launched to LEO with an Atlas V 521-class launch vehicle this spacecraft could return a 10,000-kg asteroid to the ISS in about 5.4 yr.

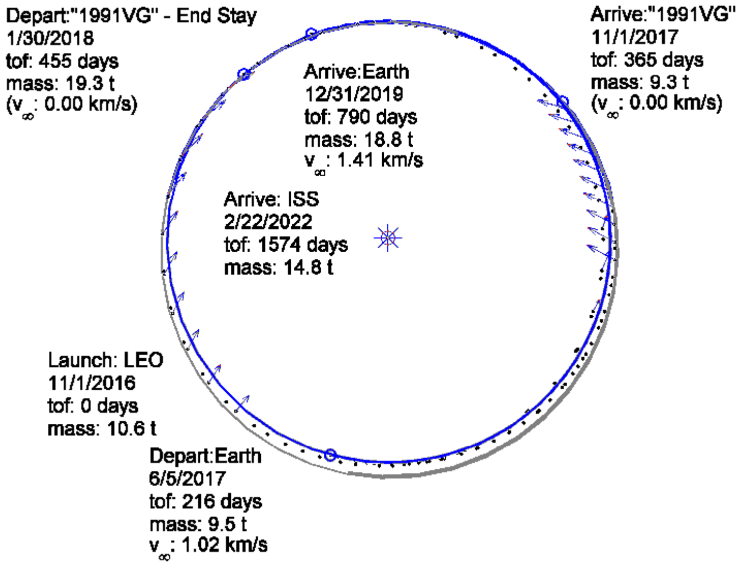

Fig. 4. Example trajectory to a “representative” NEA for a 40-kW SEP system that could return a 10,000-kg asteroid to ISS in 4.3 yr by first launching to GEO transfer orbit (GTO). The launch mass to GTO would be consistent with the performance of a Delta IV Heavy-class launch vehicle.

D. Spacecraft Mass Estimate

Our spacecraft mass estimate is based on scaling up of detailed designs previously engineered by JPL and our contractors for missions with related functionality, particularly the Dawn SEP-powered asteroid rendezvous mission[10] and a SEP-powered vehicle design from a comet surface sample return mission study. Based on our known engineering requirements, the asteroid return spacecraft would be roughly twice the size and power of the comet sample return spacecraft, allowing a reasonable extrapolation of subsystem performance and mass. Our conceptual Asteroid Return vehicle would be of a similar power level to the high-power electric propulsion (EP) demonstration mission now under consideration by NASA. The high-power EP demonstration mission could demonstrate all of the SEP technologies required for the Asteroid Return Mission concept including the high-power Hall thrusters and PPUs, the large solar arrays, and the spacecraft power distribution subsystem.

The Asteroid Return Mission spacecraft concept is dominated by the large solar arrays. The mission analysis discussed above indicates that a power level of approximately 40 kW (end-of-life at 1 AU) would be required to return a 10,000-kg NEO to the ISS in a total flight time of approximately 5 years. To this we add a margin of 10% for the SEP input power and allocate 500 W for the rest of the spacecraft resulting in a total solar array power level of 45.5 kW. The solar array is assumed to be configured in two wings of 22.75 kW each. Each wing would have a total area of approximately 71 m^2. There are multiple candidate solar array technologies that would have the potential to meet the needs of this proposed mission including, for example, a scaled-up Ultraflex array[11]. We did not select a specific array technology, but instead have specified the required specific power for the array. In our conceptual mission timeframe we expect to have an array technology with a specific power of 200 W/kg available for a launch in 2020.

The SEP subsystem would include a total of 5 Hall thrusters and Power Processor Units (PPUs). A maximum of 4 thruster/PPU strings would be operated at a time. The SEP subsystem also includes xenon propellant tanks, a propellant management assembly (PMA), and 2-axis gimbals for each Hall thruster. The PMA provides xenon at a regulated pressure to xenon flow controllers (XFCs) that then supply the propellant to individual thrusters at the required flow rates. The subsystem would include one spare thruster/gimbal/PPU/XFC string to be single fault tolerant. We assume that the thrusters incorporate recently developed technologies which mitigate channel wall erosion[12,13] so that no additional thrusters need to be added because of propellant throughput limitations.

Each thruster is estimated to have a mass of 19 kg, and operates at a specific impulse of up to 3000 s at a thruster input power level of ~10 kW. The xenon propellant tank is based on a cylindrical, composite overwrap pressure vessel (COPV) design with a seamless aluminum liner. Such tanks are projected to have a tankage fraction for xenon of approximately 4%. (For reference, the Dawn xenon tank had a tankage fraction of 5%.) A total of 8 xenon tanks would be required to store the 9,240 kg of xenon required for this mission. Each tank would have a diameter of 550 mm and is 3,500 mm long.

Attitude control during SEP thrusting is provided by gimbaling the Hall thrusters. This would provide pitch, yaw, and roll control for the spacecraft. Thrusting with the electric propulsion system would be the normal operating mode for the spacecraft. This would be the mode in which the spacecraft would spend the vast majority of its time during the mission. At other times attitude control and spacecraft translation would be provided by a monopropellant hydrazine reaction control system (RCS). The hydrazine propellant quantity required was estimated by scaling the impulse for similar functions for the proposed comet sample return mission and then adding the propellant required to despin the asteroid as discussed above. The result, as indicated in Table 2, is rather large, so future studies should consider other options including the use of a biprop system. Required spacecraft dynamics functionality also include: matching the spin state of the target body, control of close-in operations, and locating the center of gravity (CG) of the post-capture asteroid plus spacecraft stack. This functionality is similar to that which has been extensively studied in regard to rescue of errant non-cooperating satellites, and no show stoppers have been identified.

Table 2. Spacecraft mass estimate for an Atlas V 521-class launch to LEO.

Subsystem/Component	Unit Mass CBE	# of Flight Units	Total Mass CBE
Structures & Mechanism Subsystem			**375**
Ion Propulsion Subsystem (IPS)			**694**
Hall Thruster	19	5	97
Hall Thruster Gimbal	8	5	39
Xenon Pressure Management Assy	9	1	9
Xenon Flow Controller	6	5	32
Xenon Tanks	46	8	369
Latch Valves	0.1	5	1
Service Valves	0.1	5	1
Lines, Bkts, Harness, Misc	14	1	14
Power Processing Unit (PPU)	19	5	97
PPU / Thruster Harness	7	5	35
Electrical Power Subsystem (EPS)			**633**
Solar Array Wings	114	2	227
Solar Array Hold/Release Mechanism (HDRM)	10	2	20
Solar Array Drive Assembly (SADA), 1 Axis	25	2	50
Solar Array Drive Electronics (SADE)	10	2	20
Fuse Assy	10	1	10
Li-Ion Battery	68	2	136
Low Voltage Power Distribution Electronics (LVPDU)	30	1	30
High Voltage Power Distribution Unit (HVPDU)	140	1	140
Reaction Control Subsystem (RCS)			**101**
Command & Data Handling (C&DH)			**24**
Attitude Control Subsystem (ACS)			**14**
Thermal Control Subsystem (TCS)			**244**
RF Communications (Telecom)			**32**
Spacecraft Harness			**100**
Total Bus Dry Mass (CBE)			**2218**
Payload			**250**
Capture Subsystem	200	1	200
Instruments	50	1	50
Flight System Dry Mass CBE			**2468**
Xenon Mass (includes 10% contingency)			**9236**
Hydrazine Mass			**775**
Total Flight System Wet Mass			**12479**
Launch Vehicle Capability (Atlas V 521)			**13700**
Flight System Dry Mass Allocation			**3689**
Flight System Dry Mass Margin (Alloc. - CBE) / Alloc.			**33.1%**

Redundant cameras would be used for navigation to and characterization of the target body during approach and for control of capture operations. Other instrumentation is discussed below. A total of 50 kg is allocated for the cameras and other instrumentation.

The spacecraft mass estimate for capturing and returning a 10,000-kg asteroid with a 46-kW solar array beginning with a launch on an Atlas V 521-class vehicle is shown in Table 2. This mission concept has a 5.5-year flight time (see Fig. 3) and a reasonable dry mass margin of 33%. Interestingly enough, this estimate indicates that we can return 10,000 kg of asteroid material to the ISS by launching 13,700 kg to LEO, indicating that the mass of material returned is 73% of the mass launched from Earth. The Delta IV Heavy-class launch to GTO has a similar dry mass margin with approximately a year shorter flight time. Given the immaturity of the flight system design and mass estimate, these results should be interpreted as an indication that we are "in the ballpark" of being able to return a 10,000-kg asteroid using a single EELV. Very large mass margins, for example, could be obtained by launching the spacecraft to LEO using the Delta IV Heavy.

E. Approach and Docking to the ISS

After capture, the asteroid would be contained inside the high-strength bag, which in turn would be contained and stabilized inside the canister. This dual containment system would be used to prevent possible loose debris from being a hazard to the ISS. When approaching the ISS at some point it would be necessary to switch from the electric propulsion system to chemical propulsion RCS. Our preliminary assessment is that this switch should be made approximately 800 to 1600 km (500 to 1000 miles) from the station depending on the actual mass of the object and subsequent braking requirements. The large solar arrays of the SEP vehicle would need to be retracted or jettisoned prior to station keeping and docking with the ISS, with power being provided by a small auxiliary panel or batteries.

For safe docking of the asteroid at the ISS, according to ISS engineering, there are three potential docking /berthing mechanisms that might be available in the time frame of interest:

1. The Androgynous Peripheral Attachment System (APAS).
2. The Common Berthing Mechanism (CBM).
3. The international Low Impact Docking System (iLIDS).

Since the stress carrying capability of the asteroid would likely be unknown at the time of docking with the ISS, it is desirable to minimize the stressed imparted to the asteroid. Of the three options, the APAS would likely impart the largest stresses to the asteroid. The iLIDS should provide a softer berthing approach and might be the best method. To perform the docking, the spacecraft/canister would maneuver to be captured by the Station arm which would attach to a grapple fixture on the canister. The arm would then guide the spacecraft into the docking port. Other approaches would be possible and the grapple/approach details would ultimately be worked with proximity ops to determine the preferred method. Whatever method is selected, it would likely not have a major impact the spacecraft design and maneuvering capability/requirements.

F. Safe Handling of the Asteroid at the ISS

After docking, access to the asteroid could either be through the docking port directly into the ISS airlock or through port holes in the canister and bag. Both Extravehicular Robotic (EVR) and Human Extravehicular Activity (EVA) approaches could be used to gather samples from the asteroid. Asteroids of this size routinely hit the Earth and are not considered potentially hazardous objects.

G. Scientific Investigations

Scientific investigations would be performed at three different locations: in deep-space prior to asteroid capture; at the ISS; and on the ground where copious samples would be made available to analytical laboratories around the world.

Activities to be performed at the asteroid before capture. The minimum set of required analyses are those that would validate the capture and transport strategy. These are the first three measurements are listed in Table 3. In addition, since the asteroid would be totally contained at the ISS in order to avoid ISS damage due to dust and debris, access to the asteroid would be via ports / access points in the container. Therefore, an extensive set of measurements before capture would be appropriate to support later testing, planetary protection categorization, and sampling at the ISS.

Table 3. Measurements that would be required at the asteroid in deep-space.

Parameter	Measurement Technique
Essential Measurements	
Size, shape, rotation state	10-cm resolution imaging
Mass	Precision tracking
Capture	10-cm resolution imaging
Desired Measurements	
Detailed surface structure, dust	1-cm resolution imaging, radar albedo / polarization
Mineral composition	Visible / near-infrared multi-spectral imaging
Elemental composition	X-ray fluorescence spectroscopy
Internal composition and mass distribution	Radar frequency EM probes; Acoustic analysis
Radioactive element distribution	Radiation detector
Temperature, thermal inertia	Thermal infrared spectroscopy

Activities to be performed on the asteroid at the ISS. The initial activity at the ISS would likely be selecting and retrieving samples for transport to Earth. Early sampling would provide the least contaminated material for detailed analysis. Initially no sample analysis would likely be done inside the ISS. Sample locations would be chosen based on the remote sensing conducted at the asteroid combined with limited visual observation at the ISS. Sampling and packaging would be done by astronauts on EVA, analogous to lunar sampling during Apollo. This would provide valuable experience with tools and techniques, prior to the potential human mission to a NEO. These activities are listed in Table 4.

Table 4. Proposed EVA sampling activities at the ISS.

Activity	Technique
Document the asteroid thru access ports	1 cm resolution imaging
Collect samples	Hand tools, drill
Document samples	1 cm resolution imaging
Package samples	Precision-cleaned containers with ID
Pack samples for transport to Earth	Sealed container

After detailed sampling is completed, the asteroid – still in its container – would be available for *in situ* tests and analyses. These would be specific to asteroid's bulk properties, or to the space environment. Subsamples of the asteroid could also be brought into the ISS for testing and could make use of the ISS Micro Gravity Glove Box and the ISS Furnace Facility. A wide range of studies would be possible, consistent with the safety of the astronauts and the ISS including:

- Resource utilization (e.g., shaking, heating, crushing, leaching)
- Device implantation (pods/landers, physics packages, beacons)
- Albedo alteration (for Yarkovsky-based deflection)
- Cohesive forces in surface dusts and granules
- Seismic properties
- Thermal properties
- Detailed surface studies (weathering processes)

Activities to be performed on the asteroid samples on Earth. The samples would be transported to Earth and immediately placed in a dedicated Asteroid Curation Laboratory at the NASA Johnson Space Center. Subsamples would be prepared and distributed to laboratories worldwide for testing and analysis. This procedure has been successfully employed with all of NASA's extraterrestrial samples, and is specified by current NASA policy (NPD 7100.10E). These activities are summarized in Table 5.

Table 5. Asteroid Curation Laboratory activities at the NASA Johnson Space Center.

Activity	Technique
Document packaged samples	Imaging
Open sample packages	Positive pressure, flowing nitrogen glovebox
Document samples	Imaging, electronic balance
Subsample for preliminary examination	Hand tools, rock splitter, bandsaw
Document subsamples	Imaging, electronic balance
Preliminary examination	Optical microscopy, x-ray fluorescence analysis
Package samples for storage	Precision cleaned containers with ID
Store samples	Positive pressure flowing nitrogen glovebox
Track samples and subsamples	Database
Publish preliminary examination data	Website
Solicit sample requests	Website
Approve sample requests	Review committee recommendation, HQ concurrence
Distribute samples for research and development, display, education and public outreach	

III. Scaling to Larger Sizes and Other Final Destinations

The trajectory in Fig. 3 indicates that the 40-kW SEP vehicle has a total delivered mass capability back to the Earth (captured in high-Earth orbit) of about 20.1 t with a total time of flight of 1153 days (3.2 years). If this is the final destination instead of the ISS, then significantly larger (more massive) asteroids can be delivered. For our representative case, it takes 0.7 t of xenon to transport the 10 t asteroid back to the Earth and 4.3 t to spiral it from there down to the ISS. If we stop at high-Earth orbit, then we don't need the 4.3 t of xenon that makes up part of the 20.1 t mass at Earth arrival and this mass could be replace by asteroid mass. This would also reduce the launch mass by this at least this amount, i.e., to 9.4 t. This overly simplified scaling suggests we could, with the same flight system, deliver a 14.3 t asteroid to high-Earth orbit in a total flight time just over 3 years. This is significant since we now have the case where we're launching 9.4 t into LEO and can return 14.3 t of asteroid material to a high-Earth orbit, a ratio of 1.5.

However, if we relax the flight time constraint and determine how massive an asteroid we could return to high-Earth orbit in a total flight time of 5 years, the answer is an astonishing 500,000 kg as indicated in Fig. 5. This trajectory assumes the same 40-kW flight system from Fig. 3 and Table 2 beginning with an Atlas V 521-class launch to low-Earth orbit. The trajectory shown in Fig. 5 picks up after completion of the 1.6-year spiral to Earth-escape. From Table 1, a 500,000 kg asteroid is roughly 7 m in diameter.

A C-type asteroid is expected to have up to 40% of extractable volatile material and about 18% metals (mostly iron).[14] Therefore, a 500,000-kg C-type asteroid may contain approximately 200,000 kg of volatiles (water, carbon dioxide, nitrogen, ammonia, etc.) and 90,000 kg of metals (roughly 85,000 kg of iron, 6,500 kg of nickel, 900 kg of cobalt) and ~200,000 of other stuff.

SEP vehicles with power levels of order 300 kW are being considered for human exploration missions.[6] A 400-kW SEP vehicle is ten times more powerful than the 40-kW-class vehicle discussed above. Such a vehicle, if launched to LEO with a heavy-lift launch vehicle, may be capable of transporting NEAs that are of order 5,000 t (5,000,000 kg) to high-Earth orbit.

Of course, the real asteroid masses and flight times will depend on finding actual target asteroids to return, and on their orbit characteristics.

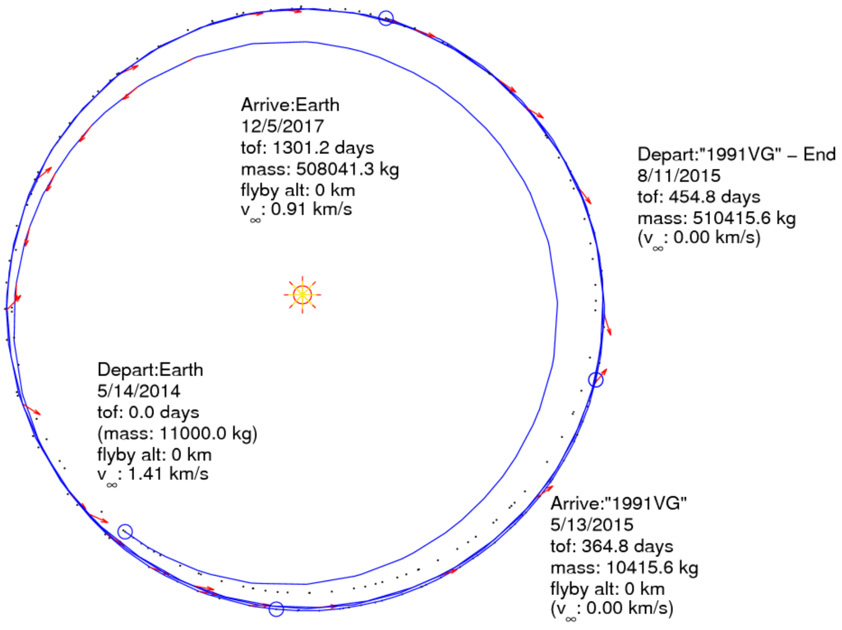

Figure 5. Example trajectory to a "representative" NEA for a spacecraft with a 40-kW SEP system. When launched to LEO with an Atlas V 521-class launch vehicle this spacecraft could return a 500,000-kg asteroid to high-Earth orbit in about 5 years.

IV. Conclusion

This preliminary study concludes that there are no show stoppers associated with returning an entire 10,000-kg NEO to the ISS in a mission that could be launched by the end of this decade. Each of the key feasibility issues have been addresses and are summarized below:

1. Reasonable projections suggest that several dozen, scientifically interesting, unrestricted Earth return candidate NEOs of the right size will be known in this time frame from which a suitable target could be selected.
2. A preliminary approach for capturing, securing and despinning the asteroid has been identified that is consistent with a broad range of asteroid characteristics.
3. Low-thrust trajectory analyses suggest that the mission could be performed from a single EELV with a total flight time of approximately 5 years and a SEP power level of 40 kW (at 1 AU).
4. This mission concept could be performed using a solar electric propulsion system of approximately the same size as that currently being considered by NASA for a high-power EP flight demonstration. High-power Hall thrusters that take advantage of recently developed technologies that enable very large propellant throughput capabilities would be required.
5. The conceptual approach outlined herein could return to low-Earth orbit a mass of extraterrestrial material that is over 70% of the initial spacecraft mass. If the target destination is high-Earth orbit, then this ratio increased to 150%.
6. Multiple approaches for docking the SEP vehicle and its asteroid cargo with the ISS have been identified. The details associated with the best approach would ultimately be worked with the ISS proximity operations team.
7. Safely handling the asteroid at the ISS would require care and planning, but is definitely feasible.
8. There appear to be no major problems with the curation of the asteroid at the ISS where numerous possible scientific and resource utilization experiments could be conducted. Asteroid material brought to the ground would be curated at the NASA Johnson Space Center where subsamples would be prepared and distributed to laboratories worldwide for testing and analysis.

9. Significantly larger asteroids could be returned to high-Earth orbit. A 40-kW SEP system launched from an Atlas V 521-class launch vehicle to low-Earth orbit with a launch mass of 13,700 kg, may be capable of returning a 500,000-kg asteroid to high-Earth orbit for an incredible 35-to-1 mass amplification factor.

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